Lateral Mixing DRI:
Turbulence-Resolving Simulations of Upper-Ocean Lateral Mixing

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LONG-TERM GOALS

This study contributes to our long-term efforts toward understanding:

- Mixed layer dynamics
- Processes that communicate atmospheric forcing to the ocean interior
- Frontal dynamics, in particular the role of surface forcing in lateral mixing
- The interaction of finescale and submesoscale upper-ocean mixing at fronts.

OBJECTIVES

The focus of modeling in this study is to quantify relationships between surface fluxes of heat, energy and momentum, the available baroclinic potential energy, the resultant vertical mixing and geostrophic imbalance, and the ensuing dependence of lateral mixing at successively larger scales on atmospheric forcing. In this year of the DRI the emphasis of my worked changed more to participating in the field program by providing a suite of shore support products from remote sensing and assimilative ocean models. This relatively minor component of the original proposal to ONR became more important to this DRI and has required a greater fraction of my effort than anticipated this year. Although it has thus, for the most part, served the LatMix DRI well this past year during a filed experiment using three vessels, modeling goals remain chief among my objectives.

APPROACH

Large Eddy Simulations of 3D large-eddy turbulence in boundary layers of depth 10m< H_{ML}<100m have enabled model-data comparisons against measurements of turbulence and dispersion. Such comparisons can critically assess the role of mixed layer dynamics and surface-driven vertical mixing in the cascades of baroclinic potential energy into submesoscale lateral mixing processes. Large Eddy Simulations (LES) have been done in close collaboration with E. A. D'Asaro and C. M. Lee, whose AESOP field experiments measure upper ocean mixing processes in the strong lateral density gradients of the Kuroshio and in a weaker front of the California Current off Monterey, during periods of varying wind and wave forcing. Field experiments for the LatMix DRI will provide further basis for

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realistic modeling efforts. These simulations incorporate virtual Lagrangian Floats, gliders and drifters, to provide a basis for interpreting these small-scale mixing measurements. In addition to LES modeling and parameterization of observed and simulated frontal regimes, Harcourt has been participating extensively in the field component of the LatMix DRI by providing a steady stream of remote sensing and regional model data to scientists in the field through the information flow (INFLO) subgroup of the DRI.

WORK COMPLETED

Providing remote sensing and ocean model imagery and data in compact form to ships during field experiments constitutes a significant effort in this year. Dubbed information flow (INFLO), a system for archiving and serving images to ships with low bandwidth capabilities, was developed out of Harcourt's prior roles in the field work of E.A. D'Asaro and Lee during the AESOP DRI. While there are many sources of data and imagery available from multiple agencies, the requirements of field program are more specific, and a consistent and unified system for framing and downloading data to scientists was necessary. This has been a service activity to the DRI carried out with important assistance from J. Molemaker and Andrey Shcherbina before and during the first field experiment in the June 2011 under J. Ledwell.

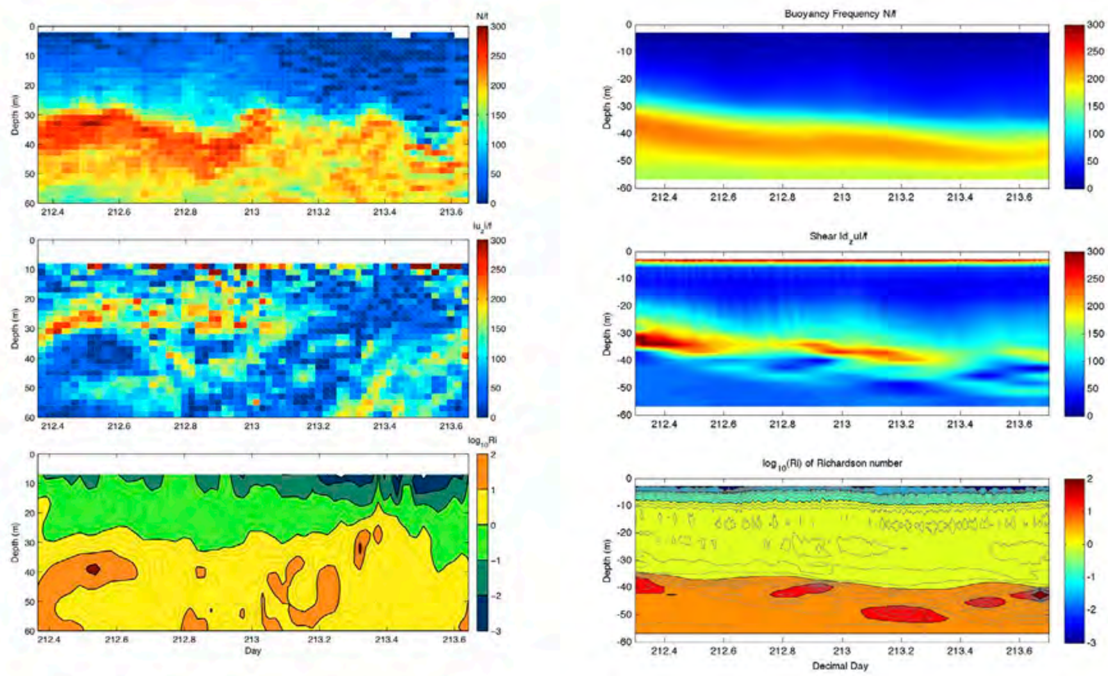
Analysis of new and previous LES model results has focused on parameterizing horizontal fluxes and TKE components in simulations of field observations made during the AESOP DRI. In addition, a collaborative paper (D'Asaro et al, 2011) on observations of a sharp front in the Kuroshio has been published in *Science*. Another paper (Inoue et al, 2010) has been published, examining mixed layer TKE budget discrepancies in wintertime Gulf Stream observations, and the possible impacts of submesoscale dynamics and the forward cascade of energy to small scales on this budget. In addition, LES results have been used for interpretive frameworks for nearly Lagrangian floats (Harcourt & D'Asaro, 2010) and semi-Lagrangian gliders (Frajka-Williams et al., 2011), papers published this year and attributable to the Typhoons DRI, this DRI, and to its predecessor AESOP.

RESULTS

While analysis of AESOP observations with D'Asaro and Lee focused first on the more dramatic measurements of the second field experiment in the strong Kuroshio front, leading to on (D'Asaro et al, 2011). Analysis of the LES modeling done for earlier observations of a weaker front in the California current have focused on simulation features that represent upper ocean lateral mixing and are sensitive to the width of the front or the LES domain. Following further analysis of the California current front measurements this year by Andrey Shcherbina, more detailed comparison between observations and LES model results has been made. These point to a process of lateral mixing that may occur within the pycnocline in the observed front that is absent in the LES (Figure 1).

The steady deepening of the LES-modeled mixed layer due to the Ekman advection of the boundary layer against the subsurface baroclinic density gradient (Fig. 1 right) is found only early in the strongly mixing comparison period driven by down-front winds. In both observations and LES, potential vorticity (PV) becomes negative in the mixed layer in the early half of this period through day 213. After that, simulation and measurements diverge, with mixed layer deepening and decreasing PV reversing in the observations, coincident with the weakening of subsurface stratification. While it remains possible that there are several unrelated coincidences involved in these observations, one possible explanation is that the deepending of the mixed layer in the front by advective adjustment

produces a PV anomaly leading to lateral mixing in the pycnocline by large scale vertical modes. Lateral mixing between the mixed layers within and on the lighter (East) side of the front led to weakening of the deep pycnocline, while vertical mixing resulted in a broader front with lower PV. This has suggested a new approach to turbulence resolving LES of this front that will be modeled in the coming year.



Observed **LES model**

Fig.1. Comparison of evolution of stability in observed (left) and LES modeled (right) front in the California current from AESOP during a period of strong mixing driven by down-front winds. Significant differences appear in the evolution of pycnocline stratification (top), shear (middle) and Richardson number (bottom). These differences coincide with the steady reduction in the observed from of negative mixed layer potential vorticity after day 213.

Some comments on the INFLO activities of this past filed season seem in order. This is generally a service activity for the DRI here and elsewhere that I've done it. I have come to it somewhat accidentally and now find I am frequently serving as shore support to generate imagery from remote sensing and assimilative ocean models that are tailored to the field experiment's interests and the limits of bandwidth at sea. Through several I have developed software that automatically searches for and produces appropriate imagery to place on a server for filed scientists to download or browse. However, in this incarnation of my shore support role in the LatMix DRI, things got much more complicated. In addition to simply producing and serving an image archive, there were loops of measurement data to pass between ships and the positions of several dozen assets of various types in the water to collate and relay to the ships for situational awareness. In addition, some scientists requested that imagery and data be formatted for presentation in Google Earth.

The most important aspects of INFLO fortunately went smoothly. My software to search for and produce imagery, formerly a bit cranky and buggy, ran largely without a hitch. This was fortuitously enhanced by the serendipitous choice of the Sargasso Sea and Gulf Stream as the area of interest, where the high concentration of high-resolution AVHRR imagery gave us 400 nearby satellite passes during the 20 day experiment, and many of these were cloud-free and useful in the areas of operation. The collection and redistribution of the positions and assets in the water, for obstacle avoidance and scientific targetting, was also largely successful. Only occasionally did communications break down with individual vessels, usually due to equipment or software on board, leading to asset positions that ceased to update. Indeed, noticing that a particular ship's position had ceased to update was often the first indication that their software or hardware needed to be repaired or reset.

Quite a few other components of INFLO, largely among things we did for the first time, either failed spectacularly or did not work well. Communications over the ships broadband connections were challenging (eg. precluding the planned use of Adobe Connect for meetings), many aspects of the investment of time in producing files for rapid use in Google Earth were underutilized or sometimes really misleading when used, and in many respects the circular flow of information between the ships and shore tripped over itself. Fortunately the data archive was also directly accessible to the ships and work-arounds were found to some of the problems. I have been formulating a list of errors made by myself and others to share at our next meeting, before the next field experiment this winter, but a principal finding is the need to work with an engineer with more extensive understanding of network communications via sattelite and the overlap of the many different operating systems used within the group.

IMPACT/APPLICATIONS

Lateral Mixing DRI results bear on the predictive skills of regional scale models with O(1-10) km resolution. At these scales the parameterizations of both vertical and lateral fluxes are not well understood or tested, especially in energetic frontal environments, or in subsurface environment where lateral mixing is driven by the relaxation of stratification anomalies produced by turbulent mixing events.

RELATED PROJECTS

One focus of the Lateral Mixing DRI is to continue a focus of the AESOP DRI to improve our understanding of mixed layer instabilties and associate lateral mixing process in a close collaboration between modeling and observations, and in particular on the combination of LES modeling and Lagrangian float observations. Typhoons DRI relies similarly on LES and LES-based models for the interpretation of Lagrangian float data, particularly where density changes along the float path due to lateral gradients can impact the relationship between Eulerian and Lagrangian turbulence statistics.

PUBLICATIONS

D'Asaro, E. A., C. M. Lee, L. Rainville R. Harcourt and L. Thomas 2011: Enhanced mixing and dissipation at ocean fronts. *Science* 15, 318-322 [published, refereed].

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Inoue, R., M. C. Gregg and R. R. Harcourt, 2010: Mixing rates across the Gulf Stream, Part 2: Implications for non-local parameterization of vertical fluxes in baroclinic surface boundary layers, *Journal of Marine Research* 68, 673-698 [published, refereed].

Frajka-Williams, E., Eriksen, C., Rhines, P.B., Harcourt, R. R. 2011. Determining vertical water velocities from Seaglider. *Journal of Atmospheric and Oceanic Technology* DOI: 10.1175/2011JTECHO830 [published, refereed].